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**ZIRCONIUM-BASED ALLOY AND METHOD FOR MAKING A COMPONENT FOR
NUCLEAR FUEL ASSEMBLY WITH SAME**

The present invention relates to zirconium-based alloys that are to constitute nuclear fuel assembly components usable in light-water nuclear reactors, such as nuclear fuel rod claddings or assembly guide tubes, or even flat products, such as grid plates.

The invention has a particularly important, although not exclusive, application in the field of the manufacture of cladding tubes for fuel rods intended for pressurised-water reactors in which the risks of corrosion are particularly high as a result of a high lithium content and possibly as a result of risk of boiling, and also in the field of strip materials used for structural components of the fuel assemblies of such reactors. The invention also proposes a method for making such components.

Patent application PCT FR99/00737 proposes a zirconium-based alloy also containing, by weight, apart from unavoidable impurities, from 0.03 to 0.25% in total of iron, on the one hand, and of at least one of the elements of the group constituted by chromium and vanadium, on the other hand, having from 0.8 to 1.3% of niobium, less than 2000 ppm of tin, from 500 to 2000 ppm of oxygen, less than 100 ppm of carbon, from 5 to 35 ppm of sulphur and less than 50 ppm of silicon, the ratio of the iron content, on the one hand, to the chromium or vanadium content, on the other hand, being from 0.5 to 30.

The invention is based on observations made by the inventors in the course of a systematic study of the intermetallic phases and the crystallographic forms of those phases which

appear when the relative contents of iron and niobium are varied while the contents of tin, sulphur and oxygen are described in the application mentioned above. It is also based on the observation, made experimentally, that the nature and the crystallographic form of the intermetallic phases containing zirconium, iron and niobium have a major influence on corrosion resistance in various environments.

In particular, it has been found that the presence of compounds having a crystalline structure with a face-centered cubic lattice, obtained owing to a proportion of iron relative to niobium sufficient to result in the presence of $(\text{Zr Nb})_4 \text{Fe}_2$, at the expense of the compound $\text{Zr}(\text{Nb}, \text{Fe})_2$ having a hexagonal lattice, and of the phase βNb , which predominate at the high Nb/Fe ratios, substantially improves corrosion in a medium having a high lithium content, such as that which exists at the beginning of an operating cycle of some pressurised-water reactors. On the other hand, the presence of the phase having a face-centered cubic lattice in too large a quantity slightly impairs corrosion resistance in an aqueous medium.

The present invention aims especially to provide an alloy which enables components to be obtained whose composition can be adapted in an optimum manner to the conditions of use provided for and whose composition is not likely to hamper the manufacturing steps excessively.

To that end, the invention proposes, in particular, a zirconium-based alloy also containing, by weight, apart from unavoidable impurities, from 0.02 to 1% of iron, from 0.8% to 2.3% of niobium, less than 2000 ppm of tin, less than 2000 ppm of oxygen, less than 100 ppm of carbon, from 5 to 35 ppm of sulphur and less than 0.25% in total of chromium

and/or vanadium, the ratio R of the niobium content less 0.5% to the iron content, optionally supplemented by the chromium and/or vanadium content, being lower than 3.

The choice of the ratio $R = (\text{Nb}-0.5\%)/\text{Fe}+\text{Cr}+\text{V}$ results from the observation that the phase having a face-centered cubic lattice appears as soon as the relation between the content of Fe (and also of Cr and V if they are present) and the content of Nb is such that R is lower than a threshold which depends slightly on the contents of other elements and on the temperature but is at most 3.

The invention also proposes a method for making a tube according to which:

- a bar is produced from a zirconium-based alloy also containing, by weight, apart from unavoidable impurities, from 0.02 to 1% of iron, from 0.8% to 2.3% of niobium, less than 2000 ppm of tin, less than 2000 ppm of oxygen, less than 100 ppm of carbon, from 5 to 35 ppm of sulphur and less than 0.25% in total of chromium and/or vanadium, the ratio of the niobium content less 0.5% to the iron content, optionally supplemented by the chromium and/or vanadium content, being lower than 3;
- the bar is water-quenched after heating at from 1000°C to 1200°C;
- a blank is extruded after heating at a temperature of from 600°C to 800°C;
- the blank is cold-rolled in at least two passes to obtain a tube, with intermediate thermal treatments at from 560°C to 620°C; and
- a final thermal treatment is carried out at from 560°C to 620°C, all of the thermal treatments being carried out in an inert atmosphere or under vacuum.

The final thermal treatment leaves the tube in the recrystallised state, which promotes creep strength, without modifying the nature of the phases. The addition of chromium and/or vanadium, which is substituted for iron and niobium in the hexagonal phase, enables the proportion of the two phases, hexagonal and face-centered cubic, to be controlled.

The alloy may also be used to produce flat elements. Those elements are also used in the recrystallised state and can be manufactured by the following sequence: a blank is produced from a zirconium-based alloy also containing, by weight, in addition to unavoidable impurities, from 0.02 to 1% of iron, from 0.8% to 2.3% of niobium, less than 2000 ppm of tin, less than 2000 ppm of oxygen, less than 100 ppm of carbon, from 5 to 35 ppm of sulphur and less than 0.25% in total of chromium and/or vanadium, the ratio R of the niobium content less 0.5% to the iron content, optionally supplemented by the chromium and/or vanadium content, being lower than 3,

the blank is cold-rolled in at least three passes, with intermediate thermal treatments and a final thermal treatment,

one of those intermediate thermal treatments or a preliminary thermal treatment before the first cold-rolling pass being effected for a long period of at least 2 hours at a temperature lower than 600°C, and

any thermal treatment following the long treatment and, in particular, the final recrystallisation treatment, being effected at a temperature lower than 620°C.

The invention also proposes the application of the above alloy to the production of components of nuclear reactors operating with pressurised water that initially contains

less than 5 ppm of lithium. Although that content then decreases rapidly, owing to its consumption in order to adjust the pH of the coolant, it may be important to avoid rapid initial corrosion.

The existence of the intermetallic compounds, which is due to the presence of iron in a sufficient quantity, including the existence of $Zr (Nb, Fe)_2$, reduces the amount of niobium precipitates in phase β which do not promote corrosion in a lithium-containing medium, but also the niobium content of the solid solution and therefore gives satisfactory resistance to uniform corrosion at a temperature of approximately $400^\circ C$, which is representative of the temperature that prevails in reactors.

The presence of chromium and/or vanadium as a very partial replacement for iron in the intermetallic precipitates of the type $Zr (Nb, Fe, Cr, V)_2$ has no marked effect on corrosion at $400^\circ C$ because chromium and/or vanadium is simply substituted for iron and/or niobium in the intermetallic compound as the chromium content increases. The improved corrosion resistance at $400^\circ C$ is maintained especially if the sum $Fe+Cr$ (optionally plus vanadium) is at least 0.03%.

To summarise, an alloy of the above type having a use in the recrystallised state to increase its resistance to the bi-axial creep of tubes and the aptitude for the pressing of sheet metal has characteristics which are adjustable by regulating the iron/niobium ratio but which are still favourable to:

- a high corrosion resistance in an aqueous medium at high temperature, which medium optionally contains lithium, the resistance being all the higher in this last-mentioned case if a high iron content is adopted, which is permitted

by a high Nb content and with an iron/niobium ratio exceeding 0.3,

- a high creep strength owing to the presence of tin which remains at a very low content and, owing to doping with oxygen, at a content lower than 2000 ppm, which then has no harmful effect on corrosion resistance.

In current reactors, the ranges given below are particularly valuable as a zirconium-based alloy also containing, by weight, apart from unavoidable impurities:

- Nb : 0.8% to 1.1% by weight
- Fe : 0.3% to 0.35% by weight
- Sn : 0.15% to 0.20% by weight
- Cr and/or V : 0.01 to 0.1% by weight
- O₂ : 1000 to 1600 ppm
- S : 5 to 35 ppm
- C : less than 100 ppm

The above characteristics and others will emerge more clearly on reading the following description of particular embodiments which are given by way of non-limiting example. The description refers to the drawings which accompany it and in which:

- Figure 1 is a ternary diagram showing the intermetallic compounds and microstructures which appear for various ranges of composition, in the case of a content of 0.2% of tin, at a temperature of from 560°C to 620°C;
- Figure 2 shows a fraction of the diagram on a large scale;
- Figure 3 shows results of corrosion tests in a lithium-containing medium on samples having variable iron and niobium contents.

The carbon and oxygen contents were substantially identical for all of the samples and were lower than the maximum values given above. The tin content was 0.2% and the sulphur content was 10 ppm.

The samples were manufactured by thermo-metallurgical operations at a temperature not exceeding 620°C, any treatment exceeding that value beyond the extrusion operation reducing corrosion resistance at high temperature.

The ternary diagram in Figure 1 shows, for Fe/Nb ratios lower than approximately 0.3, the existence of a region in which the α Zr phase (with the exclusion of the β Zr phase which is very detrimental from the point of view of corrosion resistance), the β Nb phase precipitates and the inter-metallic phase Zr (Nb, Fe)₂, which has a hexagonal structure, co-exist.

For a high Fe/Nb ratio, up to a niobium content of the order of 50%, which is higher by more than one order of magnitude than the contents used, the compound (Zr, Nb)₄Fe₂, which is face-centered cubic, also appears. The β Nb phase disappears completely only at a Fe/Nb ratio of the order of 0.6.

As will be seen hereinafter, it appeared that a high niobium content is very favourable to corrosion resistance in lithium-containing water.

The coexistence of the cubic and hexagonal phases is promoted by a Fe/Nb ratio higher than 0.3, while respecting the relation $(\text{Nb}-0.5\%)/\text{Fe}+\text{Cr}+\text{V} > 2.5$.

A precise study of the ternary diagram for the low Fe and Nb contents shows that the Nb content in solid solution develops with the Fe content, with Nb remaining constant.

As soon as the Fe content exceeds 60-70 ppm for the alloy according to the present invention, the hexagonal Zr (Nb,Fe)₂ form appears which substitutes the β Nb phase for a ratio by weight of Nb/Fe substantially equal to 2.3.

There then appears the face-centred cubic compound (Zr, Nb)₄Fe₂, corresponding to Nb/Fe substantially equal to 0.6.

This face-centered cubic phase (Zr, Nb)₄Fe₂ starts to appear for:

1% Nb	from 0.29 to 0.44% Fe
1.5% Nb	from 0.49 to 0.66% Fe
2% Nb	beyond 0.78% Fe

The diagram shows that, by simultaneously increasing the content of Nb and of Fe, a higher density of intermetallics is obtained, which promotes corrosion in a lithium-containing medium.

The influence of the Fe and Nb contents is shown more clearly in Figure 3 which gives the measurement of the weight of alloy samples after maintenance for 84 days in water containing 70 ppm of lithium at a temperature of 360°C; the measurement of the weight of a sample of Zircaloy 4 under the same conditions was 35.96 mg/dm².

The value of the simultaneous presence of a high content of niobium and iron and of the observance of the condition explained above will be immediately appreciated.